Cryobot: An Ice Penetrating Robotic Vehicle for Mars and Europa

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Abstract—NASA's desire to study and characterize the solar system will be done by in-situ robotic systems in the near term. Specific interest is focused towards finding water on Mars and understanding both the climatic and depositional history of the planet. In the case of Europa, scientists desire to unravel the mysteries surrounding the thick ice crust, its chemical properties, and subsurface ocean properties. For both Mars and Europa, the major scientific interest is whether there are signs of past or extant life in either the Mars polar ice, or the sub-ice ocean of Europa. The best way to explore either of these environments is a cryobot mole vehicle, which carries a suite of instruments suitable for sampling and analyzing the ice or ocean environments. JPL is currently developing a unique robotic vehicle, which utilizes gravity, and both passive and active heating systems to drive ice to a liquid phase change state, in order to facilitate mobility. This paper describes the science driven requirements for such a vehicle, a description of the cryobot design, and results of recent performance tests in both clean and dust laden ice. Although a radioisotope power system for a flight version of the crybot is currently baselined, no decision on the final design of the flight cryobot will be made until the environmental review process is complete. Any use of the cryobot for Mars or Europa will conform to all environmental and planetary protection requirements.

TABLE OF CONTENTS

1. INTRODUCTION

The primary focus of NASA's current planetary program revolves around Mars and understanding more about the planet's climate history—in particular, what happened to the water that once existed on the surface, and, is there still water in any abundance? Although the Mars Polar Lander crashed, it would have been the first polar sortie to the Mars South Pole to understand the polar climate history, dynamics, and look for the presence of water. The north polar cap is also of interest because of Mars Surveyor Mars Orbiter Camera (MOC) images which show a significant residual ice pack composed of circumferential dunes, layered deposits, and overlying ice deposits [1]. MOC images show hundreds of layers of 1-100m thickness. There appear to be layers within large-scale (100m) albedo bands as well. The bands extend and are individually identifiable for 100's of kilometers. This offers a very rich look at planet climate history as well as the presence of water. Similarly, Europa's highly fractured crust [2] as imaged by Galileo shows signs of a rich mineral content in areas of upwelling. Again, the Europan ice crust contains a rich history of both sub-ice and inter-ice geophysical and chemical evolution. In both cases, access to the deep ice environments to unlock the history, evolutionary processes, and potential mystery of life must employ revolutionary technologies which meet the highly constrained mass, volume, and power budgets of spacecraft today. The cryobot is one of the revolutionary technologies being developed to enable these missions.

2. DESCRIPTION OF MARS AND EUROPA ICE ENVIRONMENTS

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The climate and role of water on Mars have been receiving increasing attention in the last decade as evidenced by Mars Surveyor (which recently imaged evidence of large-scale erosion) and follow-up planet visits by Mars Climate Orbiter, and Mars Polar Lander, both which unfortunately failed. Despite previous Mars successes like Viking, Pathfinder, and Mars Surveyor, the evolution of climate and whether or not life exists or existed at one time, still remain elusive questions in the minds of scientists. Polar missions have great interest because the climate history is likely preserved in the reservoirs of ice and water. Further, the likely presence of water provides an essential ingredient for life. Ice flow, sublimation coupled with global wind patterns, sediment deposition, and wind erosion are believed to be the most important processes that shape the polar caps [1]. However, little is known about the composition, porosity, density, and stratigraphy of polar ice. These fundamental questions about planet history and possible life are best examined using a cryobot mole penetrator which can deliver both imaging and sampling instruments to the ice cap sub-surface environment. Figure 1 shows Mars Orbiter Camera (MOC) images of the North Polar Cap depositional stratigraphy as well as a relief plot showing a gentle sloping region that could support a landed probe mission.

Recent magnetometry data received from Galileo confirmed that there is indeed a salty, mineral rich ocean beneath the Europan ice crust. This recent finding is extremely important in its implications relative to containing the ingredients for extant life. We know from deep ocean and polar cap empirical data collected here on Earth, that deep hydro-thermal vents and gas bubbles trapped at the ice-water interface provide a source of nutrients for micro-organisms. If recent data are accurate about the ocean on Europa, then the possibility of a liquid ocean and subsequent ice-liquid interface, presents an opportunity for the presence of past or extant life. Again, these fundamental questions about the preservation of Europa's evolutionary history in the ice, ice/ocean chemical makeup, and possibility of finding life are best examined using a cryobot vehicle which can penetrate the ice layer and perform in-situ analysis of both the ice and ocean.

Our own polar caps here on Earth are currently of great interest to terrestrial glaciologists because of recent concern over global warming. Additionally, the Antarctic polar cap contains possible treasures of early Earth history in the form of deep-ice lakes which have been sealed off from the surface for perhaps more than a million years. One such lake is Lake Vostok [3]. Lake Vostok is located approximately in the center of the Antarctic continent and is roughly half the area of Lake Ontario. It lies at a depth of about 3km beneath the ice pack. The lake remains above freezing as a result of pressure and heat from the Earth's interior. Possible finds include micro-organisms, which have not existed for one million years on our planet's surface; possible prehistoric fossils embedded in the lake bottom material; understanding of how the Antarctic continent formed based on lake bottom stratigraphy/material analysis; and whether there are any remnants of extraterrestrial particles deposited by the flow from the ice pack over the evolution of the planet. One of the most important challenges to be faced in penetrating this lake is how to maintain its pristine character. Again, a cryobot vehicle, which can penetrate the ice pack and yet allow the hole to freeze up behind it to prevent forward contamination appears to be the best solution for meeting the contaminant-free challenge.

3. Brief History of Earth Ice Melting Systems

Work on polar ice-pack penetrators started in the early 60s with the Philberth probe developed for the Expedition Glaciology International at Greenland (EGIG). The Philberth probe was a passive heating penetrator with heaters mounted in the nose [4]. The probe was powered from the surface via a cable (tether) and was able to reach depths of 90m, 260m, 218m, and 1km. The primary scientific motivation for launching the probe was to understand subsurface ice-cap motion as a function of internal temperature fluctuations.

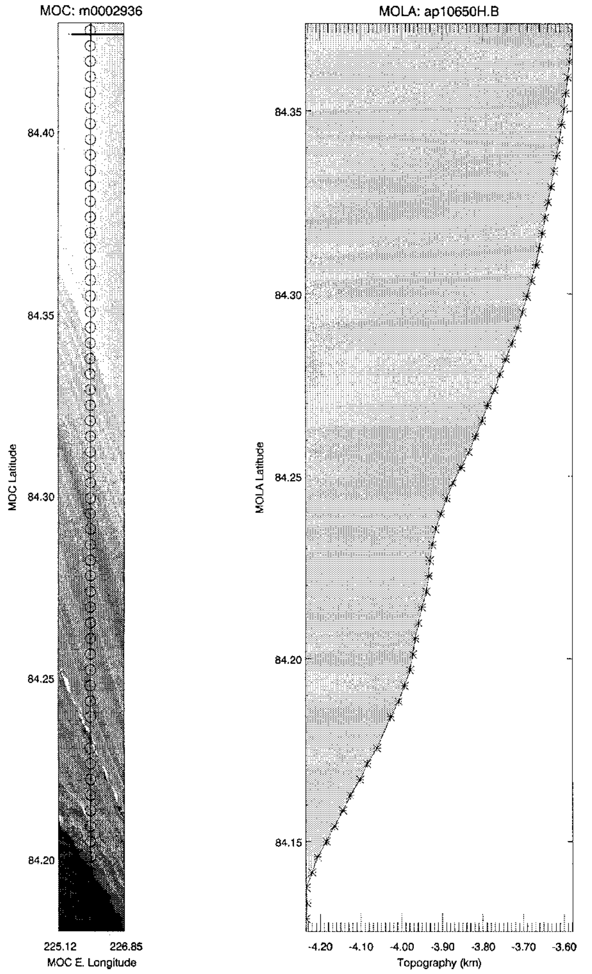


Fig. 1. Mars Orbiter Camera (MOC) images of the North Polar Cap depositional stratigraphy and a relief plot showing a gentle sloping region that could support a landed probe mission.

H. Aamot of the Army Cold Regions Research and Engineering Laboratory (CRREL) furthered the Philberth work and developed probes using a pendulum stabilization approach (i.e., the probe hangs by either a tether or a protrusion into the ice at the top of the probe and freely seeks the gravity vector as a means of steering) [5]. This probe reached depths slightly over 100m. The University of Nebraska Polar Ice Coring Office (PICO) also built a pendulum stabilized melting probe, which included a telemetry link in the tether [6]. This thermal probe also used passive heating as the primary ice phase change mechanism for mobility and allowed constant temperature/ice flow measurements to be taken during descent. The PICO probe was further modified to enable melt-water conductivity and micro-particulate measurements to be made. This probe reached depths of 100 to 200m. The PICO probe configuration represents the current state-of the art in passive melt probe design.

The thermal probes described above are typically 2.5 to 3.5m in length, with shell diameters on the order of 10 to 12cm, and mass on the order of 100s of kilograms. Power required is on the order of 3 to 5Kw. Later models, which pay the tether out from a cavity in the probe to allow the cable to refreeze behind the vehicle as it descends, have incorporated differential heating (i.e., the ability to switch heaters on and off) to enable steering. All of these passive heating probes penetrate at rates of about 2m/hr.

Ice penetration has also been accomplished mechanically using rotary cutting and coring bits (Russian Academy of Mining and Drilling, Antarctica) as well as hot water drilling [7]. The Russian ice corers have reached depths of 2 to 3km, while the hot water drilling systems have penetrated approximately 1km. While hot-water drilling is very efficient (i.e., drill rates on the order of tens of meters/hr), the energy expended in re-circulating borehole meltwater back to the surface for reheating is considerable (i.e., on the order of Mw). With the considerably larger energy input, mechanical and water jet probes are able to penetrate at rates of 3-5m/hr.

There are some significant differences between the Cryobot and existing terrestrial thermal probes. Since the Cryobot is being designed for Mars Polar Cap and Europa ice pack penetration, it must be considerably smaller in geometry as well as mass and power. The JPL Cryobot is 1 to 1.25m long, 12cm diameter, and weighs on the order of 40kg. The actual flight version of the mole will be between .8 to 1m in length and will weigh between 20 to 25kg. As a much smaller vehicle, the Cryobot melts with 1Kw thermal versus the 3 to 5Kw used by terrestrial probes. In modeling the heat transfer and fluid dynamics of the phase change process, JPL engineers found that state-of-the-art probes are actually inefficient in how they transfer heat for melting. Tight constraints on launch mass and volume drove JPL engineers to define the minimum amount of energy required to sustain the melt process. Additionally, while terrestrial thermal probes are manually controlled from the surface by an operator, the Cryobot will be a fully self contained robotic vehicle with sufficient on-board state sensors, imaging, and computing to enable autonomous control and fault recovery. This advanced vehicle design is discussed in detail in the following sections.

4. CRYOBOT DESIGN DESCRIPTION

4.1 Definition of Fundamental Ice/Penetration Issues

The Cryobot development effort at JPL was initiated in the fall of 1998, and culminated in a preliminary ice probe design for Europa, which looked very promising. The Cryo-Hydro Integrated Robotic Penetrator System (CHIRPS) is a fully autonomous robotic mole penetrator system for melting through an ice-pack projected to be 3-10km thick [8]. The probe is 1m in length and 14cm in diameter. The primary energy source baselined in the preliminary design is radioisotope thermoelectric generators (RTGs) which provide 1Kw thermal of direct melt energy. Thermoelectric converters provide electric power to drive the vehicle control electronics, state sensors (i.e., inclinometer, rate, temperature, pressure, odometry), and in-situ science instruments. The nose and shell each have 4 quadrant heaters for passive melting and differential heating for steering. A forward-looking acoustic imaging system mounted in the vehicle nose detects obstacles and the ice-liquid interface. The probe can sample melt-water as it descends, or separate into two halves as it approaches the ice-liquid interface and allow the "hot end" with instrument pods to continue to descend on a tether and drop into the ocean. The upper half of the vehicle containing the vehicle control and communication electronics refreezes in the ice and acts as an anchor. Once in the ocean, the biochemistry instrument pods are jettisoned and allowed to float up to the ice-liquid interface where the liquid is sampled for bio-signatures. Data is transmitted back to the primary upper half of the probe via pod tethers. The total science data package is relayed back to the surface lander via mini-RF ice transceivers which were dropped off like "bread crumbs" as the probe descended [9, 10]. While RF transceivers are required for Europa ice, the ice pack at the north polar region of Mars is layered, and the subsequent science is rich enough in the upper layers to enable a penetration mission using a tether (i.e., hundreds of meters vs. kilometers).

CHIRPS provided a template for the Cryobot developed under NASA's Code R research program. In designing the Cryobot, it became clear that the team needed to take a harder look at the phase change fluid dynamics problem from two fundamental viewpoints:

1. Understand the fundamental relationship between ice structure/phase change dynamics and selective heat transfer such that a minimal heating approach triggers mobility rather than using an "unlimited" heat-input approach, as currently employed by terrestrial ice thermal probes.
2. Understand the basic physics of ice structures and interstitial contaminant loading relative to how they affect heat transfer efficiency and subsequent vehicle progression—identify both directional control/ contaminant management strategies as well as define at what point vehicle progression is impossible.

These two research areas represent the current FY'00 focus of the Cryobot modeling and prototype development activity at JPL. Results of the modeling, and tests to validate the vehicle dynamic models, are provided later in this paper.

4.2 Cryobot Design Architecture

Based on the results of the fluid and energy modeling, it was determined that the most efficient way to create the phase change state from ice to water was to input just enough heat to initiate melt. Since water is a good insulator, raising the temperature significantly above freezing resulted in a increase in the meltwater jacket around the vehicle and a subsequent decrease in heat transfer to the actual ice interface [11]. Although counter-intuitive, the addition of more heat does not necessarily increase the melt rate proportionally. The model firmly established that 1Kw thermal input, at the vehicle-ice interface, was the minimal amount of energy required to maintain a 1–2-mm water jacket around the vehicle and sustain a .5–1-m/hr melt rate in extremely cold ice. In warmer ice, similar penetration rates can be achieved with half the amount of power. A volume assessment of vehicle electronics, heaters, sensors, communication tether, and science instruments resulted in a required vehicle size of at least 12cm diameter, and 1–1.25m long. The fluid modeling revealed that this sized vehicle was reasonable since even in cold ice (i.e., -100 °C), the melt plume would not refreeze until 1.25m behind the vehicle—this meant that the vehicle would not become entrapped. These configuration parameters formed the basic design envelope for the Cryobot and also confirmed that, indeed, a flight design in the ≤ 1-m length constraint was feasible. The following primary components make up the complete probe:

1. Nose
   - Water jet nozzle
   - Acoustic imager (4 transducers)
   - Four quadrant passive resistance heaters
   - Heat conductive copper inserts
   - Ceramic insulation (between heaters)
2. Pump bay
   - Melt-water pump
   - Pump motor
   - Melt-water reservoir
   - Immersion heaters (2)
   - Water jet plumbing
3. Pressure vessel
   - Forward/aft bulkheads (o-ring sealed)
   - Control electronics/cabling
   - Science instruments (2)
   - Imaging/UV laser window
   - Primary tether connector (male)
   - Shell heaters (4)
4. Tether bay
   - Copper/fiber optic power and com tether (.100 dia., nominally 300m long)
   - Tether connector (female)
   - Tether brake and encoder

The Cryobot design in shown in Figure 2. Table 1 displays the primary Cryobot design parameters based on existing design and modeling/test performance data. The functional block diagram is shown in Figure 3.

Table 1. Cryobot Design/Penetration Parameters (Phase 1 Design)

Design Parameter	Value
Test ice temperature	-10degC
Available melt power	6–.8Kw
Cryobot length	1.25m
Cryobot diameter	12cm
Penetration rate (measured) • Passive melting • Active melting	 .4m/hr 1m/hr
Water temperature (inlet)	5–6 °C
Water temperature (nozzle)	20–25 °C
Return water pressure	1–2bar
Jet velocity	10–20m/sec
Jet flow rate	1–1.5liters/min
Jetting efficiency	80-90%

When all nose heaters are on, a full kilowatt thermal is applied to heating either the passive heaters or the active water jet. This operation allows the probe to descend vertically. The combined probe nose and reservoir/pump bay allows the probe center-of-mass to be slightly forward, thus, making the probe nose heavy and stable (like a lawn dart). Figure 3 illustrates the basic operation of the vehicle. The current design has two micro-controllers. The "controller" shown in Figure 3 is responsible for the primary command interface and power management/ switching of the on-board heaters. The "sequencer" is a higher level micro-controller which does the vehicle state assessment based on the state sensor inputs. Temperature/pressure data (ambient and vehicle) allow decisions to be made about the depth and type of ice the vehicle is melting through (e.g., if the passive nose heater temperature starts to increase, the ice is more broken-up and fractured causing lower heat conduction), this signals a decision to reduce current to the heaters. Similarly, ambient temperature/pressure increase can be extrapolated to probe depth. Vehicle tether odometry and encoder-rate data also give depth and vehicle penetration rate information. The 2-axis inclinometer provides vehicle orientation data and allows heading corrections to be executed. Heading corrections are executed by differentially heating one side of the nose/shell while turning off opposing heaters (only passive heaters are involved in steering). Water reservoir volume data (using a capacitive float sensor) also provides data on the type of ice the vehicle is melting through (i.e., if the ice is broken-up and fractured the melt-water will be lost to the surrounding ice cavity and the reservoir will not fill), which allows decisions to be made about when to use passive melting versus when to use active melting. Pressure sensor feedback from the water pumping circuit provides data on sediment loading as well as water jet velocity and flow rate. Last, the acoustic imager provides obstacle information and allows decisions to be made about whether a heading change is required due to a hard obstacle like a rock, or whether a sediment lense in being approached, signaling a decision to turn on the active water jet system. Acoustic imaging in ice is an additional research area related to the Cryobot development effort

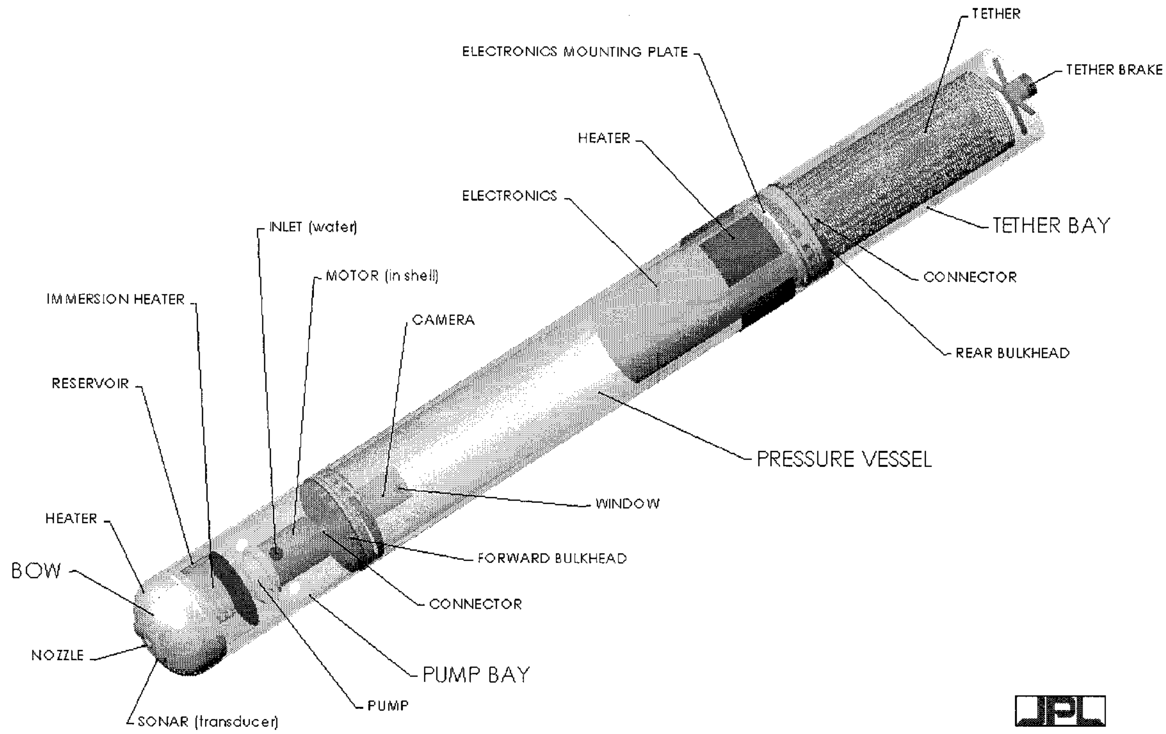


Fig. 2. Cryobot Overview.

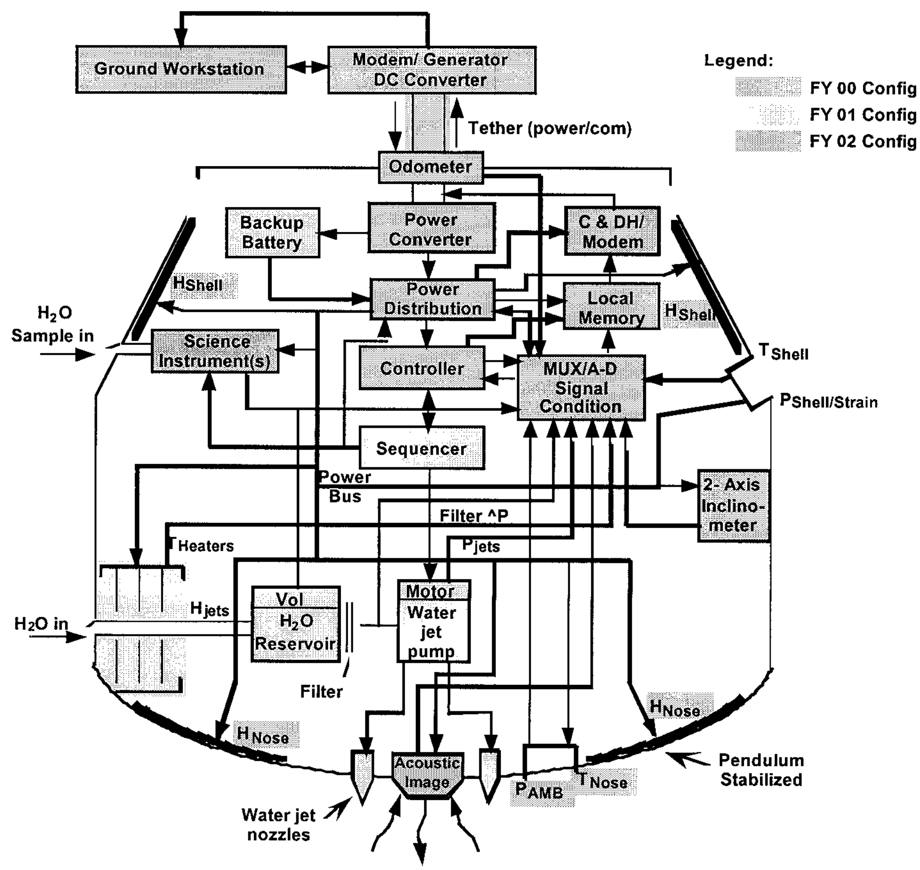


Fig. 3. Cryobot Functional Control Block Diagram.

and will be initiated starting in FY'01 and will continue into FY'02. The actual electronic control system shown in Figure 4 for the FY'00 probe contains the basic power converters/switching, controller and signal processing interfaces for the various state sensors, but does not contain the sequencer micro-controller for closed loop autonomous control.

Figure 3 also shows a science instrument interface to the overall control system. Although a sampling port is shown in the figure, the current design is to have a window in the pressure vessel which provides an equivalent sampling interface for examining the ice borehole walls and melt-water as the vehicle descends (see Figure 2). Currently, the two science instruments picked are a 100-micron camera with flash, and a UV laser/spectrometer. The camera will be imaging ice structures and sediment, and the UV spectrometer will be examining deep ice bio-signatures, which fluoresce under UV light. As with the acoustic imaging, the science instrument element of the Cryobot development effort is slated for FY'02. It should be noted that the science instrument suite is being developed under a separate JPL research activity associated with two other ocean probes; Lo'ihi Underwater Volcanic Vent Mission probe, and Deep Ocean Vent Experiment. This section provided an overview of the vehicle design and operation. The software control system architecture is discussed in the next subsection.

4.3 Cryobot Control System Design

The Cryobot can be controlled in three operational modes—manual, passive heating, and active water jetting. The manual mode is applicable only to Earth-based applications where there is an operator monitoring the state of the probe in real time (e.g., Antarctica Lake Vostok). In this mode there is no autonomous behavior executed by the Cryobot; all control is done by the operator. Based on the sensor data (temperature, pressure, odometry, inclinometer, etc.) returned, the operator controls the Cryobot by sending commands from the ground station to the probe to set the state of the appropriate actuators (heaters, pump, brake). All decisions are made by the operator. The control flow for manual mode operation is depicted in Figure 5.

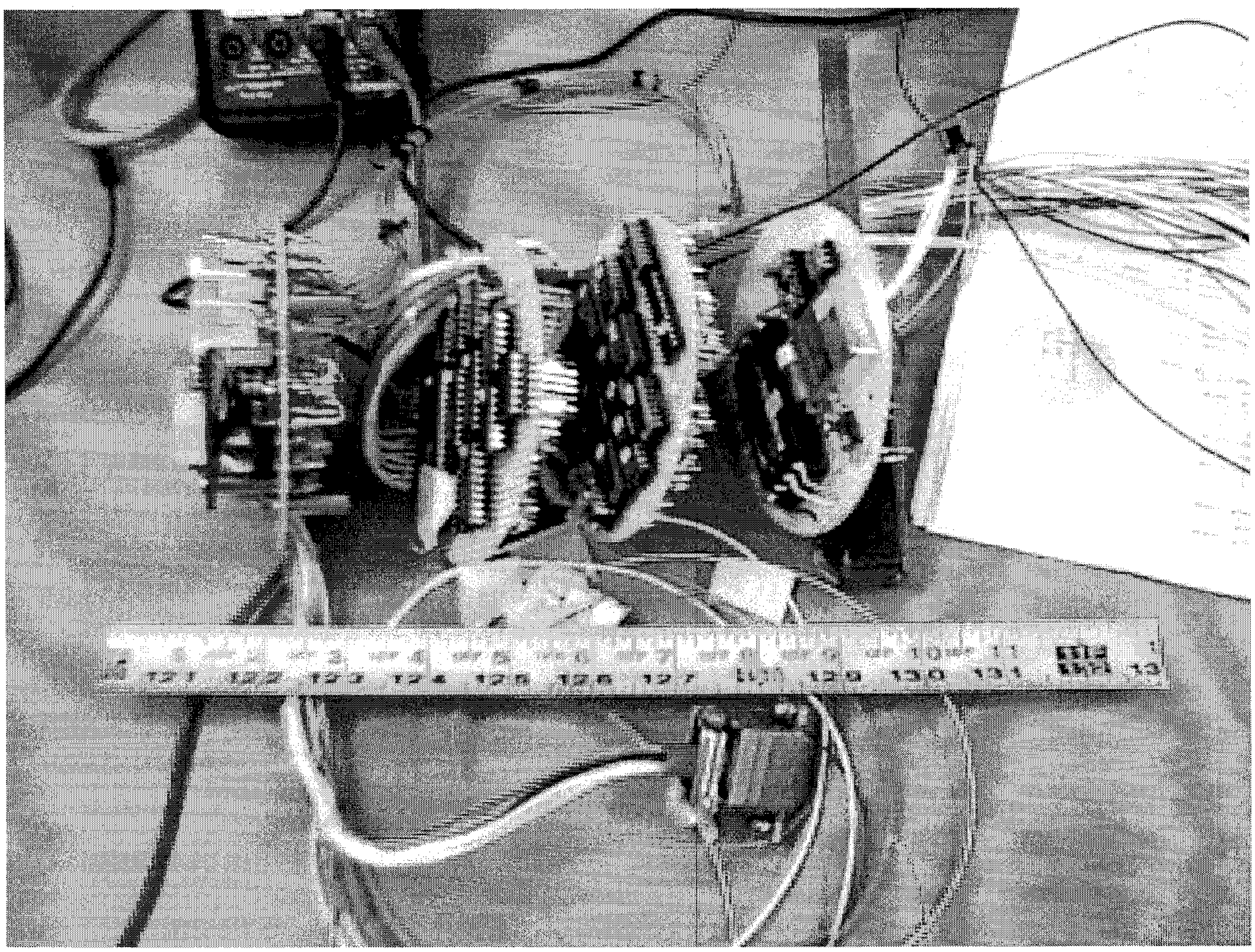


Figure 4. Cyrobot Electronic Board Stack.

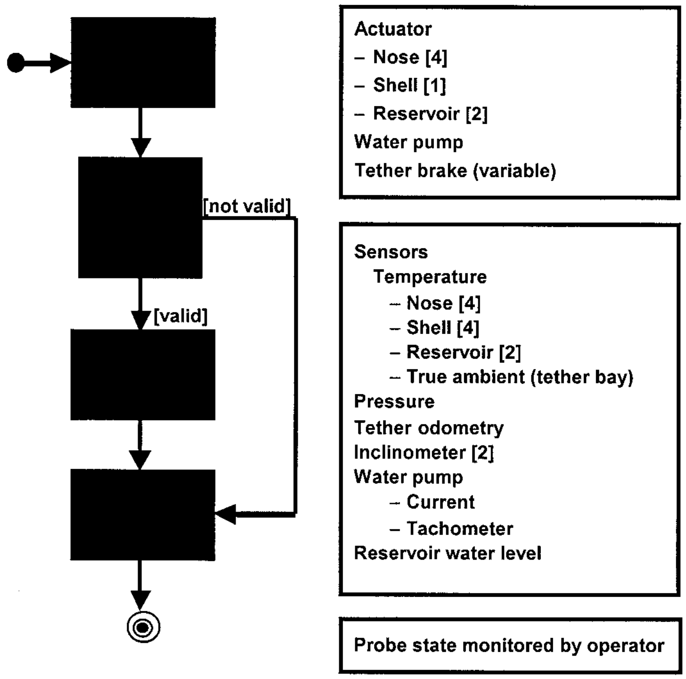


Fig. 5. Manual Mode Control Flow.

The passive heating operational mode is used for melting through firn and for steering the probe around obstacles buried in the ice. In this mode the operator sends a move command to the probe which can be either a move to a specified position or orientation. The command parameters must be within limits achievable by the probe; the probe can only move down and the orientation is limited. The Cryobot control software computes the position and orientation of the probe from pressure, tether odometry, and two-axis inclinometer data. The depth of the probe in the ice is proportional to pressure. Tether odometry is a measure of the total distance traveled. The inclinometer measures the probe angles relative to the two horizontal axes (x and y) and indicates the angle of the probe with respect to vertical. Odometry and inclinometer data are integrated over time to determine the actual path traversed by the probe.

Steering is achieved by differential actuation of the nose and shell heaters which changes the orientation of the probe as it moves through the ice. Thus, movement along the x and y axes is achievable as the probe moves down. If obstacle avoidance is enabled, the probe uses the acoustic imaging system to autonomously detect obstacles and modifies the commanded trajectory to steer around the obstacle. Once clear of the obstacle, the probe resumes the commanded trajectory. Passive heating control flow is depicted in Figure 6.

The active water jetting operational mode is used in dense ice past the firn and is the most efficient melting mode. As in the passive-heating mode, the operator sends a move command to the probe, but the command is restricted to moving down a specified distance. The controller monitors the state of the water reservoir and once it is full and up to temperature, the water pump is turned on. While the water-jetting system is active, the water temperature in the reservoir is monitored and the heaters turned on as needed to maintain the desired temperature. The pump load is also monitored via the motor current to detect if cavitation is occurring. If it is, the pump is shut down until the water reservoir is full at which time the pump is reactivated.

To achieve the most efficient melting, the distance from the front of the probe to the water-ice interface must be maintained at the optimal distance. This distance is estimated by the acoustic imaging system, and the drag produced by the tether brake adjusted to maintain the optimal distance. Tether drag is also adjusted based on the tilt of the probe and descent rate. Note that the tether system is only applicable to the Earth-based research probe (and possibly a Mars probe); a different braking system will be required for the Europa application. The control flow for the active water jetting operational mode is depicted in Figure 7.

The behavioral model of the Cryobot control system is shown in Figure 8. After power on and initialization, the probe waits in an idling state for a command to move. Upon receipt of a move command, the appropriate heaters and/or water pump are turned on until either the command is successfully completed or a non-recoverable fault condition is detected at which time the probe returns to the idling state. If the fault is a recoverable one, the control system will first recover from the fault and then continue executing the current command.

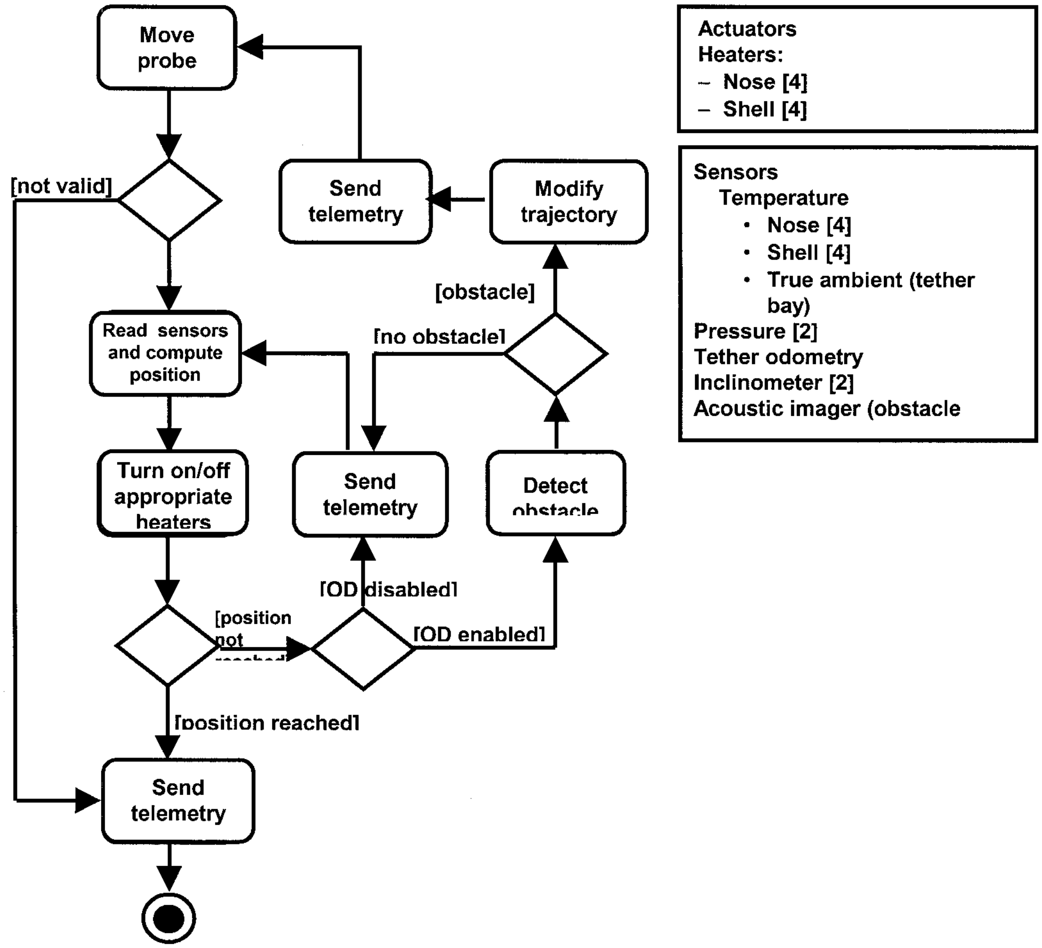


Fig. 6. Passive Heating Mode Control Flow.

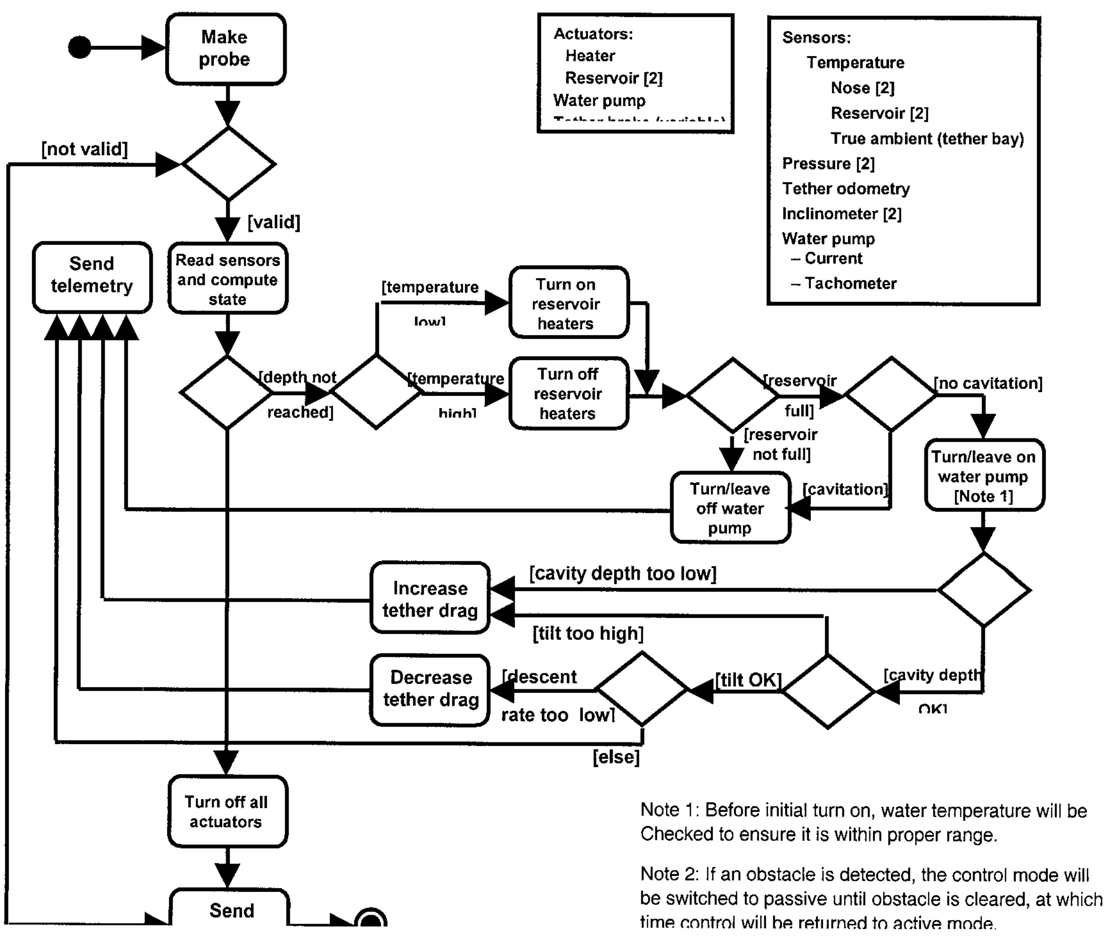
5. Results of Cryobot Performance Testing

As stated in Section 4, the focus of the FY00 research and development effort was to derive and validate an accurate model of the fluid dynamic and heat transfer processes. Once validated, the model would be used to optimize the vehicle design. Indeed, this was the first major accomplishment of the research task [11]. Figure 9 shows the projected penetration rates for a 1Kw thermal probe in different temperature ice and also displays the corrected value for likely penetration rates in Europan ice based on empirical test data (i.e., note that the .5-m/hr rate was corrected to .3m/hr). Most importantly, the vehicle dynamic modeling accurately predicted melt performance for both passive and active phase change processes [11]. Using a prototype probe of known geometry (particularly frontal area equivalent to the model, i.e., 12cm), ice with known properties (both ice structure and temperature, i.e., -10 °C), and known energy input (i.e., .6 to .8Kw), and known water jet temperature/flow rates (i.e., 25 °C at the jet outlet/1 liter/min respectively), the team was able to test and validate the predictions of the fluid and heat transfer models and obtain melt rates of .5 to 1m/hr.

The model and lab tests were used to establish the probe power requirements, vehicle size (diameter, length), and functionality. The prototype probe shown in Figure 10 was tested with a split-nose, two-heater configuration. Similar to the four-quadrant nose design, the split nose used a ceramic fin to split the two hemispheres and prevent heat transfer between hemispheres during heater switching and steering. The water jet nozzle was inserted in the ceramic web along the axial centerline of the nose to accommodate the active melting subsystem. It should be stated up front that the custom heaters designed to provide 250w thermal had not been delivered yet by the vendor. Therefore, off-the-shelf standard heaters were employed and run at lower power to prevent burn-out. The actual probe that will accommodate the full suite of acoustic sensors, high-temperature custom passive heaters, pump/reservoir motor, instruments, electronics, and tether is shown in Figure 11.

The primary test of the complete system was to melt through a 5-m ice column. Figure 12 shows the ice tower and probe melting through the ice column. The test results are summarized in Table 2.

Fig. 7. Active Water-jetting Mode Control Flow.



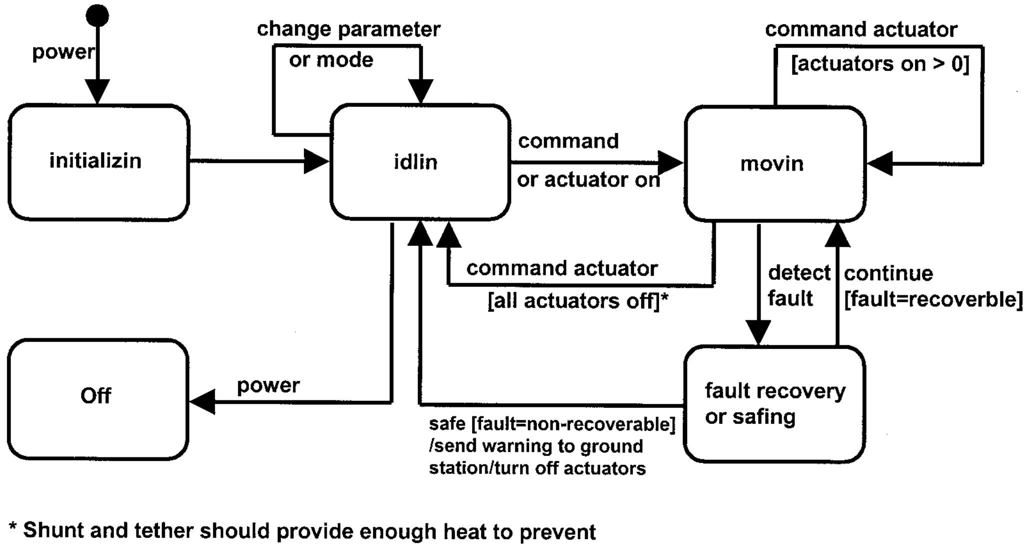


Fig. 8. Cryobot Control System State Chart.

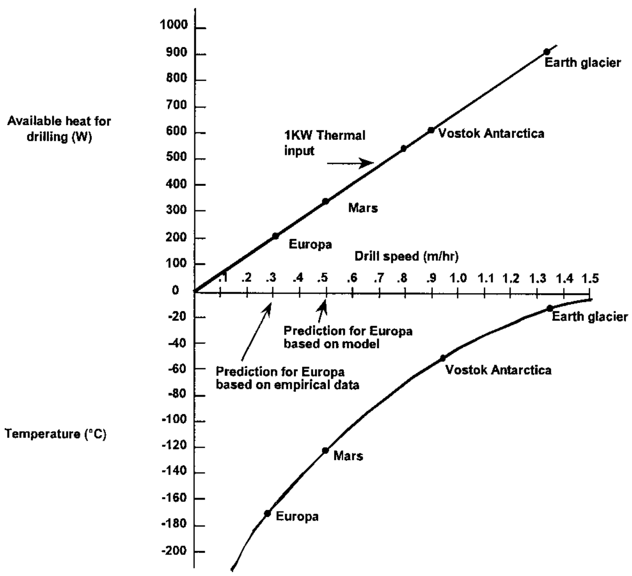


Fig. 9. Ice Penetration as a Function of Temperature and Pressure.

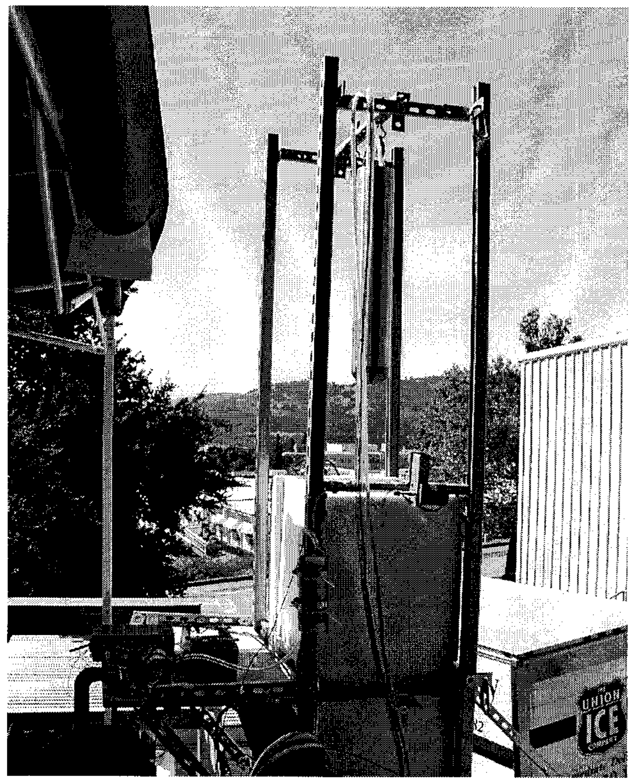


Fig. 10. The Prototype Cryobot Probe.

Table 2. Summary Results of Cryobot Performance Tests.

Test Parameter	Results/Observations
Total melt distance	5 m (plus 1 later short melt

	of 3 m)
Total elapsed melt time	11.2 hrs
Avg power	.418 Kw (range: 240–536w)
Avg descent rate • Passive melt rate • Active melt rate	43.4 cm/hr (range: 34–57 cm/hr) 34.5 cm/hr 60 cm/hr (@ water-jet temp of 30 °C; 1 liter/min.)
Vehicle attitude control • Correction #1 • Correction #2	Made 2 planned attitude corrections • Corrected 3° off-vertical drift moving ~10° in opposite direction • Corrected 7° over-shoot back to vertical
Vertical travel during correction • Correction #1 • Correction #2	 28 cm 8 cm
Observed correction dynamics	*
Variable ice conditions	
• Firn ice (low density) passive rate • Firn Sediment ice (1–10 mic, 5% vol) passive rate • Clear ice (high density) passive and active rates	• 60 cm/hr • 60 cm/hr (micron scale sediment remained suspended and did not appear to adhere to nose of probe and cause heat transfer barrier) • 60 cm/hr (ice at 0 °C)
* Heater element actuated was on side of adverse tilt. This allowed the melt cavity on that side to advance and exceed the diameter of the nose. At that time, the melt regime was able to initiate heat convection along the leading edge of the shell and allow the melt regime to increase in volume and slowly creep up along the shell. This convection process broke down the ice barrier on side of adverse tilt and the vehicle was able to follow its gravity vector and slowly move back towards vertical.	

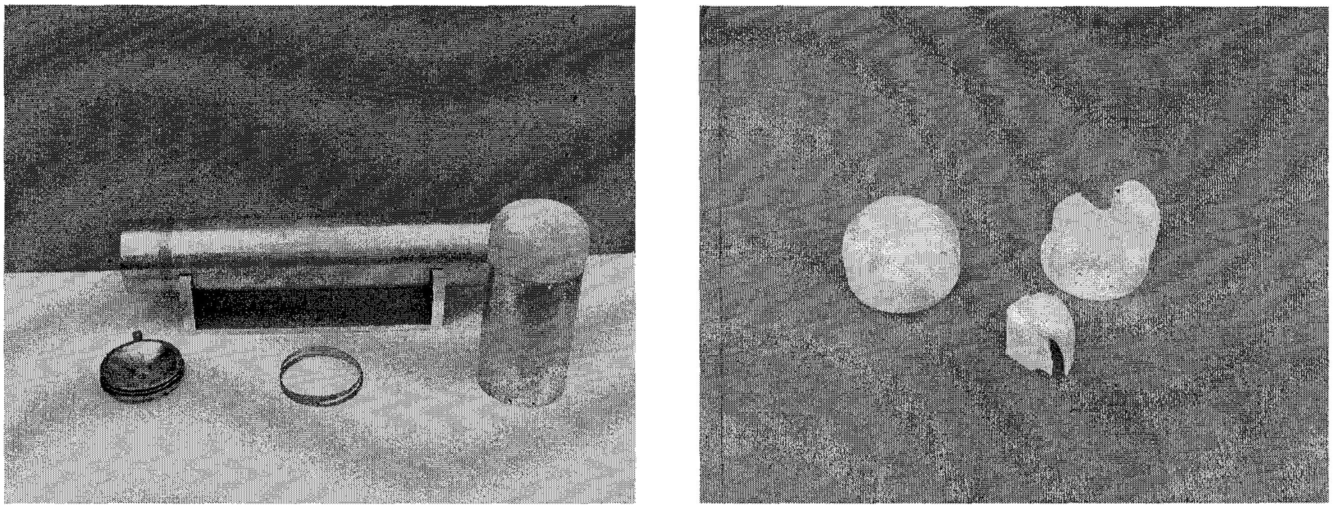


Fig. 11. Disassembled FY'01 Cryobot Probe with Nose Details.

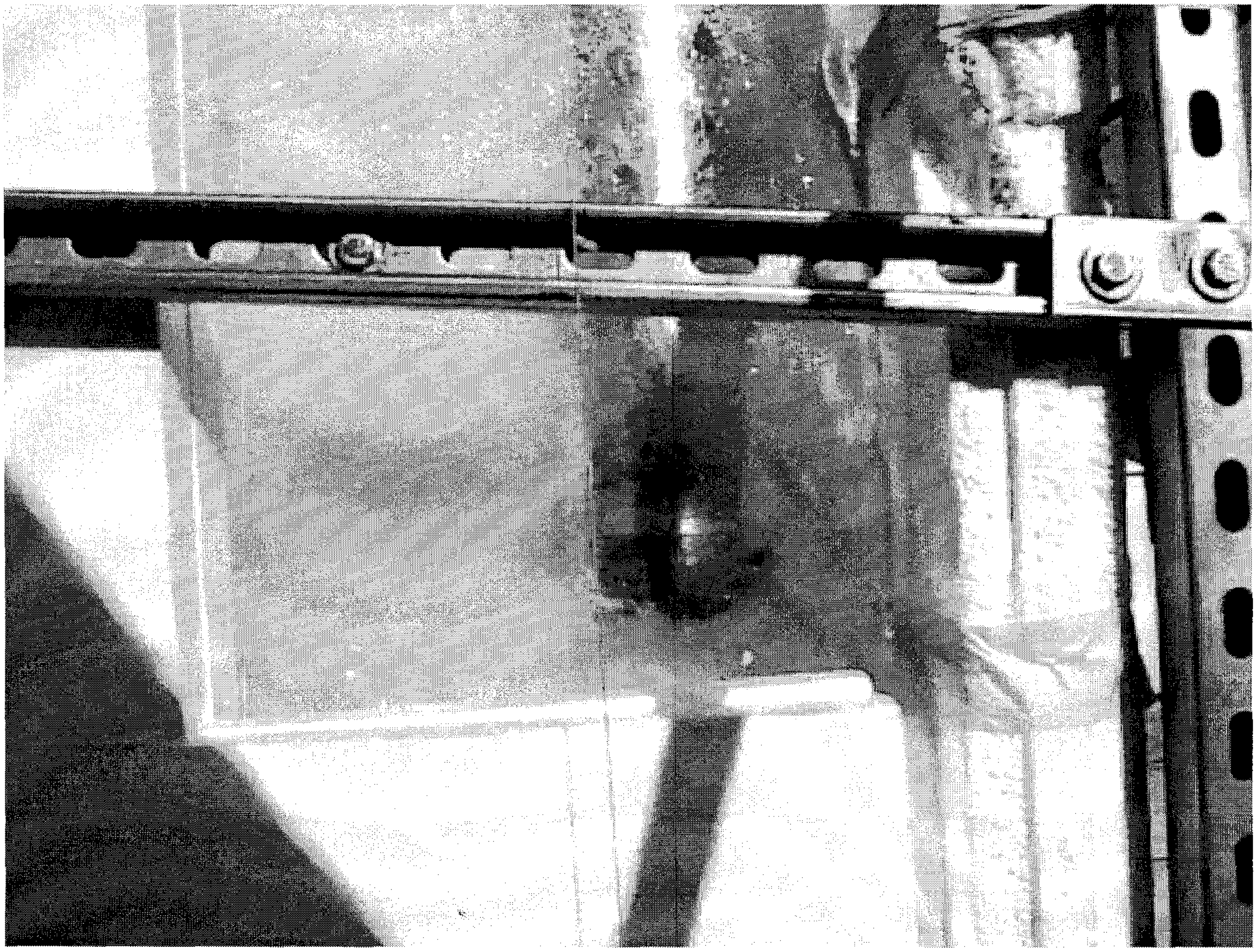


Fig. 12. Ice Tower and Probe Melting through the 5-m Ice Column.

6. CONCLUSIONS

In conclusion, the FY00 research not only developed and validated the fluid dynamic and heat transfer models, but the team was successful in designing, building, and testing the first prototype cryobot system. The test results were of particular importance in that in- roads were made into understanding the dynamics of steering as well as the importance of water jet vortices in the transfer of heat to the melt front and debris removal. The prototype probe will also be tested over a range of short melts in Antarctica to obtain melt rate data in actual pack-ice (testing to be done by Dr. H. Englehardt, California Institute of Technology, Department of Geophysics). Current plans for FY01 include continued modeling and testing of sediment-laden ice. The team will also complete the assembly of the full probe system (i.e., the active melt subsystem, full suite of vehicle state/control sensors, state assessment/sequencer micro-controller). The acoustic imaging research will be initiated in partnership with an industry partner, as will the tether design. FY'02 research and development will include the final integration/test of the acoustic imaging system, tether, a suite of two science instruments, followed by performance of a deep descent (100–300m) in actual pack (dirty) ice.

7. ACKNOWLEDGEMENTS

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9. BIOGRAPHIES

Wayne Zimmerman has been a senior engineer at the Jet Propulsion Laboratory/California Institute of Technology, for more than two decades. He received his B.S. in Fluid Dynamics with a major in Aerospace Engineering from Case Institute of Technology, Cleveland, Ohio in 1969. He received his M.S. in System Engineering/ Management from the University of Southern California, Los Angeles, California in 1972. He has been working in robotics for 20 years and was the Project Element Manager (PEM) for the Mars '98 Polar Lander robotic arm. He was the Lead Avionics Engineer for the Mars '01 microrover and robotic arm. He is currently the lead engineer for the Mars/Europa Cryobot Task. The author is also the Lead Engineer for the JPL Center for In Situ Exploration and Sample Return (CISSR). He has been responsible for spearheading advanced sampling, sample handling, and sample return system designs, which will enable out-year in situ missions to extreme environments like Europa, Venus, Titan, and comets.

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Jason Feldman is a member of the engineering staff at the Device Research and Application Section at the Jet Propulsion Laboratory. He received his B.A. in Physics from the University of California at Berkeley. At Lawrence Berkeley National Laboratory, he worked with Professor Paul Richards on the Millimeter Anisotropy Experiment (MAX). In addition to his key project—the design, fabrication, and implementation of high-speed, radiation-hard serial data communications systems for a high-altitude NASA-NSBF balloon-borne telescope—he was responsible for the set-up of a new laboratory and calibration facility, optimization of the analog electronics, and coordination of systems compatibility with collaborators. He joined the California Institute of Technology in 1998 as an assistant engineer with Professor Axel Scherer and then joined JPL in 1999. He invented the Atmospheric Electron X-ray Spectrometer and leads the experimental development of this instrument in collaboration with T. George and J. Z. Wilcox. He is a co-inventor, with J.Z. Wilcox and T. George, of a miniature ring orbitron ion pump. He develops new instruments and sensors for in situ planetary exploration, bringing them from the conceptual phase to laboratory research and field operation. Jason brings a wealth of engineering expertise and practical experience in the area of design, fabrication and testing of vacuum, mechanical, electronic, and cryogenic systems. He was the cognizant engineer for the Patch Plate dust adhesion experiment, to be flown on the Mars '03 lander as part of the MECA payload. He is currently the mechanical engineer for the Cryobot Active Thermal Probe development project., which is developing a robotic probe to carry out sub-glacial exploration in Antarctica.